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**ULTRASONIC EVALUATION OF HIGH
VOLTAGE CIRCUIT BOARDS**

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ABSTRACT

Preliminary observations indicate that an ultrasonic scanning technique may be useful as a quick, low cost, nondestructive method for judging the quality of circuit board materials for high voltage applications. Corona inception voltage tests were conducted on fiberglass-epoxy and fiberglass-polyimide high pressure laminates from 20° to 140° C. The same materials were scanned ultrasonically by utilizing the single transducer, through-transmission technique with reflector plate, and recording variations in ultrasonic energy transmitted through the board thickness. A direct relationship was observed between ultrasonic transmission level and corona inception voltage. The ultrasonic technique was subsequently used to aid selection of high quality circuit boards for the Communications Technology Satellite.

INTRODUCTION

Advanced power electronics systems require materials that are capable of withstanding increasingly severe operating environments. One mechanism by which electric power sources deteriorate is through excessive corona. Conditions such as high voltage, high temperature, and high vacuum encourage corona discharges, which can jeopardize the reliability and long life performance of the electrical system (1). Actually, corona discharge can occur at either high or low voltage levels depending on the type of insulating material utilized and the environmental conditions encountered. It is important, therefore, that the insulating materials chosen for a particular application be designed and produced to withstand the most severe operating conditions for the specified period of time.

High voltage circuit boards are generally made from high pressure laminates. Evaluation of the laminates may be performed by running corona tests according to ASTM Standards D 1868 and D 2275 (2, 3). These tests can provide a good measure of the dielectric

strength of the panel if the test is carried out under conditions similar to the final application. However, since corona tests can only be performed at discrete locations, it must be assumed that the bulk material properties are the same as those of the samples tested. Because of variables inherent to laminate fabrication, this may not necessarily be a valid assumption. In addition to its inability to perform 100 percent inspection, corona testing is time consuming, relatively expensive, and poses a degree of electrical hazard to the operator. Thus, it would be advantageous to supplement the corona test with a simple, fast method of scanning candidate circuit board materials in their entirety, to obtain a measure of the degree and uniformity of dielectric properties.

Therefore, an investigation was initiated to obtain preliminary information on the applicability of ultrasonics as a tool for evaluating high pressure laminates. Ultrasonic scans were made by utilizing the single transducer, through-transmission technique with reflector plate, and recording variations in ultrasonic energy transmitted through the board thickness. A 5 MHz transducer and commercially available ultrasonic equipment were used. The specimens were fiberglass-epoxy and fiberglass-polyimide high pressure laminates, representative of high voltage circuit board materials used in space-flight electronic systems. Corona inception voltage was also measured at discrete points on the specimens and the degree of correlation between the ultrasonic and corona test results was determined. Subsequently, the ultrasonic test method was extended to help select circuit boards for space-flight hardware.

TEST PROCEDURES

Test Specimens

The materials tested were high pressure laminates which were being considered for use in the high voltage

section of the power processing unit in the transmitter experiment package (fig. 1) for the Communications Technology Satellite (CTS). Samples were obtained from panels of NEMA grades G-10 and G-11 fiberglass-epoxy, and of fiberglass-polyimide (sometimes referred to as G-30). Hereinafter, these materials will be referred to as G-10, G-11, and G-30, respectively. The G-10 sample was not traceable since it was from a general stock. The two G-11 samples, although from the stock of two different flight programs, originated at the same laminate manufacturer. The G-30 panel was obtained from the same lot of material ultimately used for the CTS flight hardware. All samples were the same thickness, nominally 2.36 mm.

The preparation of the samples for corona testing typically consisted of scrubbing the surface with freon followed by a 4-hour vacuum bake at 120° C. Two types of corona test specimens were prepared. The type 1 specimen was chosen to simulate surface mounted hardware encountered in the CTS design (4). Specifically, two 4.7 mm diameter solder balls located on one surface, 51 mm apart, were held in place near the board surface with a nonconducting epoxy adhesive. This configuration is illustrated in figure 2(a). The process used to prepare the adhesive was identical to that used for the flight equipment. The solder balls were nominally 3 mm from the board surface, well filleted with the adhesive. The leads were #20 wire insulated with 20 kV silicone.

The type 2 specimen was used to perform spot tests on isolated regions of the test panels as illustrated in figure 2(b). The test specimen was placed between and in contact with two 19 mm chrome-plated copper balls positioned directly opposite each other. The lead from the upper ball consisted of a 12 mm diameter copper tube threaded into the ball. The lower ball and other remotely positioned support balls were in contact with a metal base plate which was connected to the corona tester with a silicone insulated lead.

Corona Test Procedure

The corona test data presented in this paper were obtained under laboratory atmospheric conditions using commercially available corona testers in the AC 60 Hz or DC mode, whichever gave the lower corona inception voltage (CIV). All data represent 5 picocoulomb CIV maximum discharges. The voltages were read from the calibrated voltmeter on the tester. An air circulating oven with corona-free feed-throughs was utilized for the elevated temperature tests.

Ultrasonic Inspection Procedure

The principles of nondestructive inspection by ultrasonics are described in detail in references 5 and 6. This section briefly outlines the test procedure used to evaluate the ultrasonic transmission characteristics of the materials in this investigation.

Basic system. - The basic inspection system is depicted by a block diagram shown in figure 3. A commercially available flaw detector formed the heart of the system. The transducer, specimen, and reflector plate were placed in a tank of water and arranged as shown in figure 4. The water serves as a coupling media for transmission of ultrasonic waves between the three components. The transducer was threaded into a manipulator rod connected to a mechanized scanning and indexing unit which was used to scan the total specimen area. The recorder pen was mechanically tied to the scanner to provide full scale permanent recordings (C-scans) on electrosensitive paper.

System operation. - The pulse generator was operated at a rate of 1.5 kHz with a pulse time of less than 1 microsecond. The electric pulses cause the piezoelectric crystal in the transducer to generate envelopes of ultrasonic waves. Between pulses, the transducer acts as a receiver for ultrasonic energy reflected from discontinuities in the travel path. These echoes are reconverted to electrical energy, rectified, and displayed on a cathode ray tube as voltage spikes vs. time. The voltage amplitude is proportional to the intensity of the ultrasonic waves reflected back to the transducer. Because the velocity of sound is relatively constant in a given material, the position of a voltage spike on the CRT time scale is a measure of the distance between the transducer and the reflective surface. The signal of interest can thus be isolated by a time gate and recorded.

Wave propagation. - Figures 3 and 4 can be used to illustrate the propagation of ultrasonic waves during test. All interfaces that separate media of differing density and sound velocities act as reflectors of acoustic energy. The waves emanating from the transducer travel through the water, specimen, and the reflector plate. At each interface, part of the energy is reflected back towards the transducer. The signal of interest is the CRT voltage spike which corresponds to the reflection off the top surface of the reflector plate. The intensity of this received signal is modified by the presence of the specimen. The waves must pass through the specimen twice, losing part of the energy

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each time by virtue of surface interactions and attenuation by internal microstructure. Variations in fiber lay-up in composites, as well as internal voids, are causes of attenuation, and result in loss of signal intensity received by the transducer. Different specimen materials and specimen cures can also result in different degrees of attenuation.

The top surface of the steel reflector plate was flat ground and ultrasonically checked to assure uniformity of its reflective qualities. The surfaces of both the reflector plate and the test specimen were cleaned with alcohol to minimize possible variations in transmitted or reflected energy levels due to variations in surface cleanliness. In many instances, slightly warped specimen panels had to be supported in a rigid fixture to assure that all parts of the specimen surfaces were perpendicular to the direction of ultrasonic wave propagation. Before performing each C-scan, the flaw detector amplifier settings were checked by comparing the amplitude of a signal received from the reflector plate after traversing a water path of known length. In this case the water path was 7.5 cm and the signal received from the third reverberation was set at 100 percent full scale on the CRT. Thus, the water path serves as a reference standard. This reference standard choice was arbitrary, and was made primarily for its convenience and reproducibility. The third reverberation, rather than the first, was set at full scale because this allowed the signal amplitude to be in the range of 20 to 100 percent of full scale when test panels were inserted between the transducer and the reflector plate. Note that the third reverberation was used only when setting up on the reference standard. During inspection of circuit board panels, the first reflected signal from the reflector plate, after passing through the specimen, was utilized for evaluation purposes.

Transducer selection. - The choice of transducer is governed to a large extent by the capability of the test specimen to transmit ultrasonic waves. Short wavelengths (high frequency transducers) are more readily attenuated by the test material than are long wavelengths (low frequency transducers). Thus, thick test panels may require that transducers with a low center frequency be used just to assure that ultrasonic waves penetrate the material. On the other hand, low frequency transducers are less sensitive to the presence of small flaws in the material. To obtain the optimum sensitivity, therefore, a compromise must be reached between frequency and energy loss in the material, and this generally must be done experimentally. For this investigation a flat (not focused) transducer with a center fre-

quency of 5 MHz and piezoelectric crystal diameter of 6 mm was used. With this transducer, the theoretical minimum detectable flaw size in the test material is of the order of 0.3 mm. However, clusters of smaller voids such as porosity in fiber reinforced composites can be detected since the cluster can have the same effect as a large void. Higher frequencies up to 10 MHz could have been utilized but, since the ultrasonic waves were required to pass through the specimen twice, it was decided to go with the lower frequency.

RESULTS AND DISCUSSION

Ultrasonic scans were made by utilizing a single transducer, through-transmission technique with reflector plate and observing variations in ultrasonic energy transmitted through the panel thickness. Corona inception voltage (CIV) was also measured at discrete points on the specimens and the degree of correlation between the two tests was determined.

Correlation of Test Results

The results of CIV tests with type 1 specimens are plotted in figure 5. The figure illustrates the necessity for evaluating candidate circuit board materials at actual operating temperatures. The G-11 and G-30 materials exhibited values of approximately 21 and 22 kV at room temperature while the G-10 specimen measured about 17 kV. The G-10 CIV level dropped off rapidly with increasing test temperature to 3 kV at 65° C. The G-11 and G-30 board materials were significantly more stable over the temperature range; the CIV levels at 120° C were approximately 14 and 18 kV, respectively. The two G-11 specimens exhibited slightly different CIV values over the temperature range, which may be attributable to somewhat different manufacturing procedures by the supplier.

These CIV results indicate that all of the G-11 and G-30 materials were suitable for applications in the Communications Technology Satellite power processing unit, which operates in the range of 11 to 13 kV at 90° to 120° C. However, the G-10 material was not acceptable for use at these temperatures.

The materials were ultrasonically scanned over 100 percent of their area to obtain a measure of the ultrasonic transmission characteristics of the materials. Typical results in the form of ultrasonic C-scans are presented in figures 6 and 7. Figure 6 contains data obtained with the same G-10 and G-11 specimens used to produce the CIV data in figure 5. The

C-scans were made on electrosensitive paper which produces power sensitive graytones. Thus, the density of the graytone is proportional to the voltage at the pen, which in turn is proportional to the energy level of the ultrasonic waves after passing through the specimen. It can be seen from the C-scans that the G-11 panel No. 1 (fig. 6(a)) exhibits the best overall ultrasonic transmission properties, closely followed by G-11 panel No. 2 (fig. 6(b)). Both G-11 panels provide far better transmission than the G-10 panel No. 3 (fig. 6(c)). Thus, better ultrasonic transmission, as evidenced by the C-scans in figure 6, suggests higher CIV values as indicated in figure 5.

Similar, but less dramatic, correlations were noted within individual specimens that demonstrated varying transmission levels at different points. Table I shows CIV test data obtained with the type 2 specimen. In these tests, which were performed after the ultrasonic C-scans were made, the electrodes were placed on opposite surfaces of the specimen in zones exhibiting either high or low ultrasonic transmission levels. The measurements were made on the same G-10 and G-11 panels for which data are shown in figure 5. In any given board, the table shows that the region of high transmission had a higher CIV value than the region of relatively low transmission. For example, in G-11 panel No. 1, a region with an ultrasonic transmission level of 90 percent corresponds to a CIV of 30 kV, while another region with a transmission level of 50 percent had a CIV of 25 kV. However, for a given transmission level (e.g., 50 percent), the CIV values are not equal in all three specimens. This indicates that, until more information becomes available, ultrasonic transmission should not be used as an absolute measure of CIV values, but rather as a qualitative indicator of relative dielectric properties.

The precise reasons for the apparent correlation between CIV and ultrasonic transmission have not yet been ascertained. More developmental work is required to establish all of the parameters which cause both CIV and ultrasonic attenuation levels to vary in fiber reinforced composites. One thing that is known, however, is that the existence of porosity in a laminate is an undesirable structural element in that it can reduce both CIV level as well as mechanical strength. It has also been shown (?) that there is a direct relationship between ultrasonic attenuation and void content and/or delaminations. Therefore, potentially low CIV due to structural anomalies such as voids can be expected to be revealed by ultrasonics, particularly if void content exceeds about 0.5 percent.

Applicability of Ultrasonic Method

Currently, the greatest value of the ultrasonic scanning technique becomes evident when it is used as a tool for mapping a specific panel to permit utilization of the best areas for application to high voltage components of power electronics. This technique was utilized to help select all flight quality fiberglass-polyimide circuit board panels for the 11 kV power supply on the Communications Technology Satellite launched in January, 1976. An example of such a map is shown in figure 7 which contains black and white C-scans of two G-30 panel segments intended for use in the CTS. Preliminary CIV data (plotted in fig. 5) showed that fiberglass-polyimide was the best candidate material for this application. Since it was not possible to obtain CIV data at all points on the samples, an ultrasonic inspection of all the available material was performed in an effort to pinpoint possible trouble spots. All dark regions in figure 7 represent areas where the voltage level on the CRT was more than 80 percent of full scale, while the white areas outline regions where the voltage was 80 percent or less (the reference standard voltage level was 100 percent). The actual circuit boards were then cut from the best segments so as to avoid the regions corresponding to the white areas on the C-scan.

It should be noted that all regions indicated by the white spots are not necessarily bad since the cutoff level was somewhat arbitrary. For example, many of the white spots on panel No. 4 were just below the black-white threshold (as indicated by the imprinted numbers) and thus need not have been avoided if material were in short supply. The same panel, however, showed one white spot with a reading of 40 percent full scale which certainly should be avoided unless a CIV test indicates otherwise.

Further developmental work must be performed before the ultrasonic technique can be utilized for measuring the ability of a material to resist corona discharge on an absolute basis. As indicated earlier, an inverse relationship exists between the degree of porosity and both CIV and ultrasonic transmission levels. Other factors such as chemistry and cure times can also influence the electrical and ultrasonic characteristics of materials, and it is entirely possible that the relationships could have opposing effects (e.g., increase ultrasonic transmission while decreasing CIV). If such was the case, porosity in certain proportions along with changes in chemical make-up could result in canceling effects on ultrasonic transmission, with

resultant failure to reveal regions of circuit boards with low CIV. Such an investigation was beyond the scope of the present work.

CONCLUSIONS

The observations noted in this investigation, although preliminary and essentially qualitative in nature, suggest that a scanning technique which measures relative ultrasonic transmission can be used to evaluate relative dielectric properties of circuit board materials. These measurements, together with standard electrical and mechanical tests currently utilized, offer a potential for greater reliability of components intended for power electronics packages such as that used in the Communications Technology Satellite.

Factors such as porosity, chemistry, and cure times can influence both the electrical and ultrasonic characteristics of materials, and it is possible that the factors could have opposing effects on corona inception voltage. Thus, further work is necessary to evaluate the effects of these fabrication variables individually before ultrasonics can be used as an absolute method for measuring corona inception voltage level.

Although it is not recommended that conventional methods of testing circuit board materials be dropped in favor of ultrasonic evaluation, the latter method offers certain advantages over corona testing. The advantages are. (1) 100 percent check on all material is possible, (2) the test is relatively fast and inexpensive, (3) the inspection can be performed with commercially available equipment, and (4) the inspection operation is relatively simple and poses no safety hazard to the operator as can be the case with high voltage tests.

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TABLE I

VOLTAGE TO INITIATE 5 PICOCOULOMB CORONA DISCHARGES ACROSS SPECIMEN THICKNESS

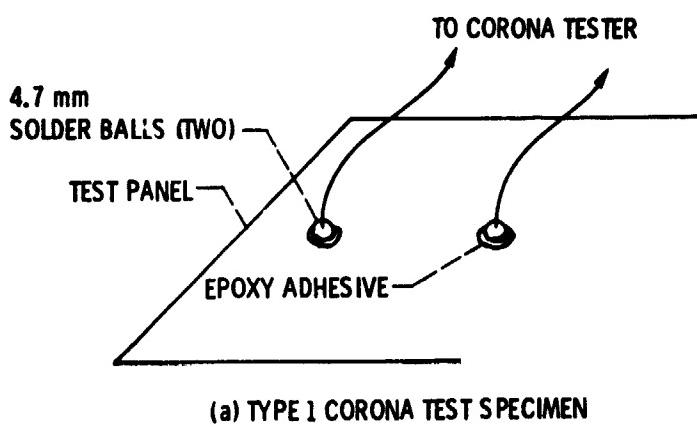
[Tests run on regions of specimens exhibiting either high or low relative ultrasonic (U/S) transmission. All materials are fiberglass-epoxy.]

Test specimen	Density, kg/m ³	Overall U/S transmission level, percent full scale (CRT)	Specific U/S transmission level, percent full scale (CRT)	kV
G-11, Panel No. 1	1938	High	90 50	30 25
G-11, Panel No. 2	1938	Medium	90 50	25 20
G-10, Panel No. 3	1854	Low	50 30	12 8

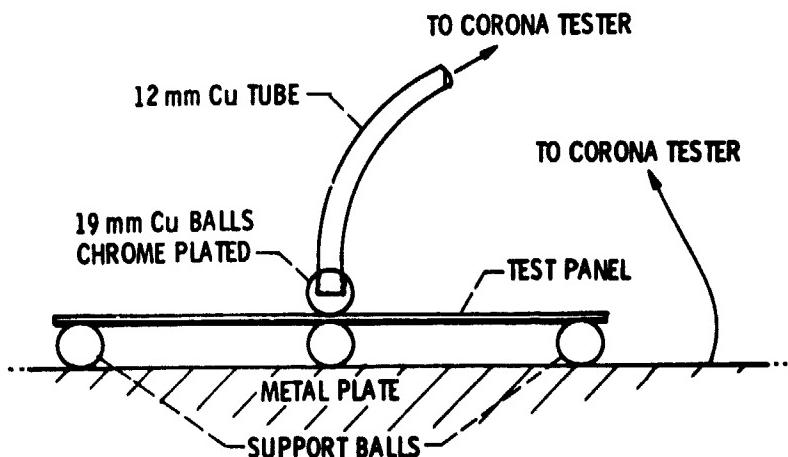
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Figure 1. - Transmitter experiment package for Communications Technology Satellite.



(a) TYPE 1 CORONA TEST SPECIMEN



(b) TYPE 2 CORONA TEST SPECIMEN

Figure 2. - Test specimen configurations used to measure corona inception voltage values.

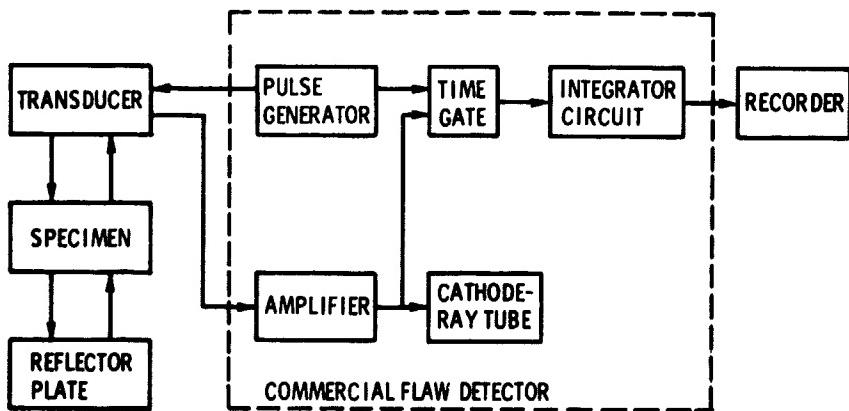
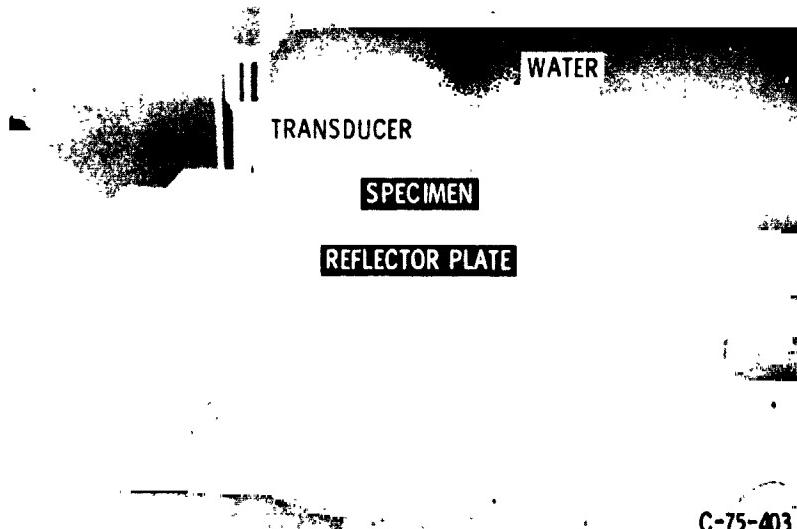


Figure 3. - Ultrasonic inspection system utilizing the single transducer, through-transmission method with reflector plate.



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Figure 4. - Arrangement of the ultrasonic transducer, steel reflector, and the circuit board material specimen during ultrasonic immersion inspection.

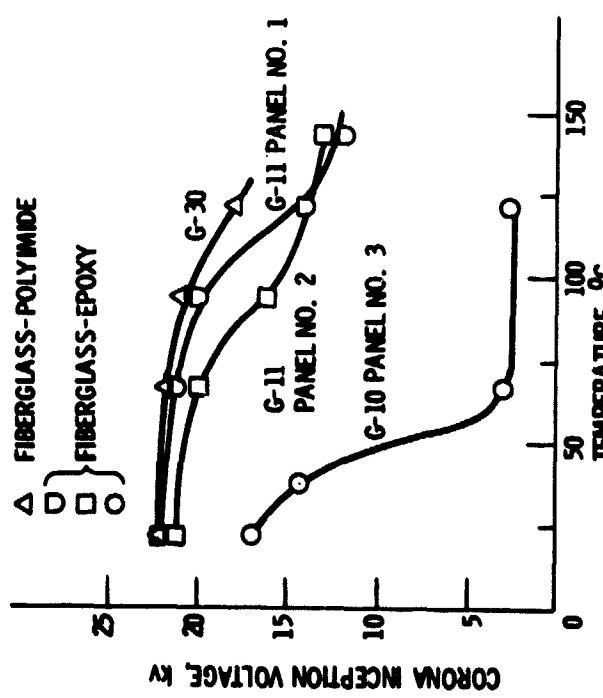
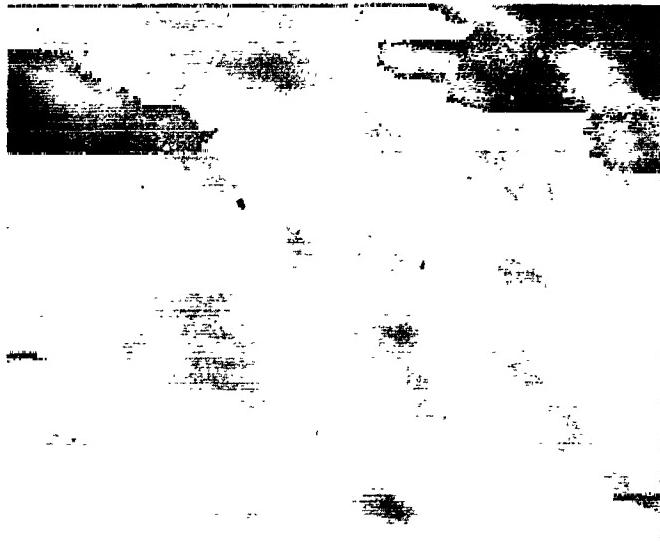


Figure 5. - Voltage required to initiate 5 picocoulomb discharges between two 4.7 mm diameter solder balls bonded with epoxy to one surface of test specimen. Distance between electrodes was 51 mm. Tests performed in air. Data points represent single measurements.

(a) PANEL NO. 1. NEMA SPECIFICATION G11. RELATIVELY GOOD ULTRASONIC TRANSMISSION.

Figure 6. - Ultrasonic C-scans showing varying levels of ultrasonic transmission through 2.36 mm fiberglass-epoxy high pressure laminates. The darkness of the scan lines is proportional to the level of transmitted energy.





(D) PANEL NO. 2. NEMA SPECIFICATION GII. SLIGHTLY LOWER ULTRASONIC TRANSMISSION THAN PANEL 1.

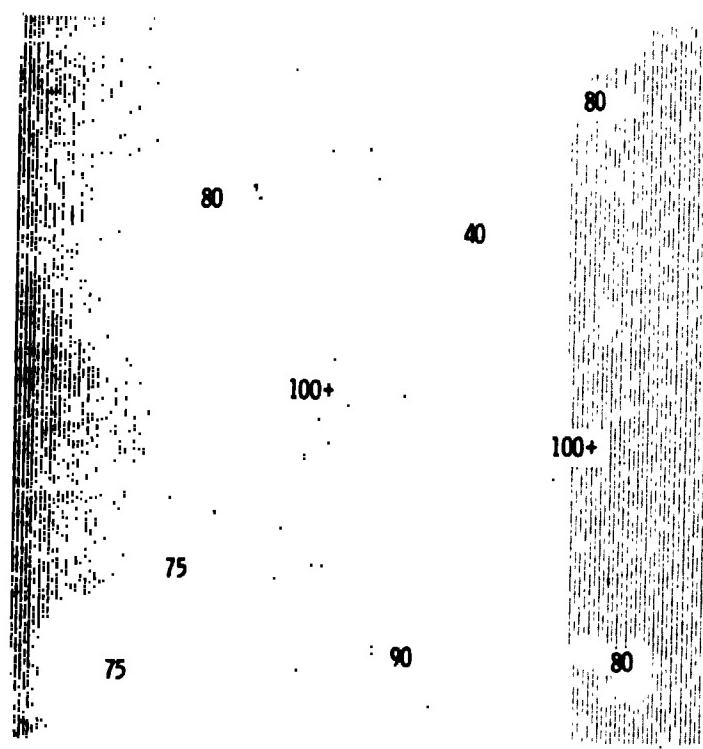
Figure 6. - Continued.



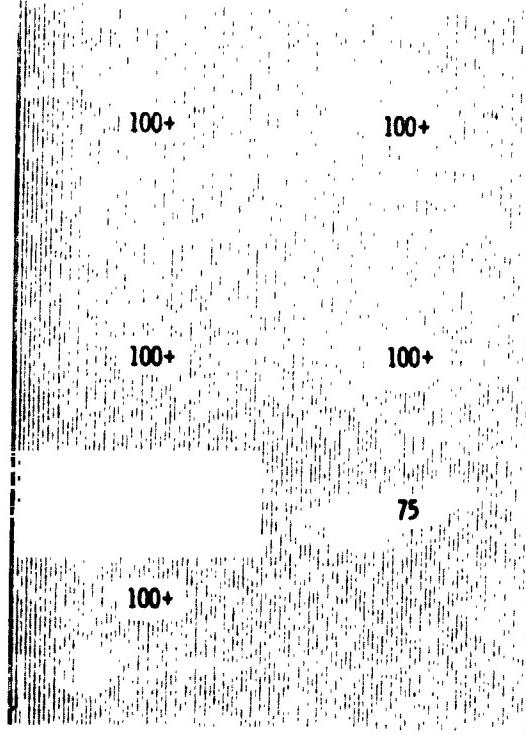
(C) PANEL NO. 3. NEMA SPECIFICATION GIO. RELATIVELY LOW ULTRASONIC TRANSMISSION.

Figure 6. - Concluded.

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(a) PANEL NO. 4.



(b) PANEL NO. 5.

Figure 7. - Ultrasonic C-scans of fiberglass-polyimide high pressure laminates showing acceptable areas (dark) and unacceptable areas (white). Numbers indicate relative transmission levels based on scale of 0 to 100.